Attempting to Explain the Cosmic-Ray Spectrum

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Outline

1. What is the energy spectrum of cosmic rays?
   -- concentrating on galactic cosmic rays

2. Crude explanation of the spectrum

3. High-energy CR ($10^{12} - 10^{17}$ eV) raise problems

4. Power requirement revisited

5. Efficient shock acceleration in SNR
   Shocked gas is hot but non-Maxwellian

6. Acceleration with cosmic-ray modified shock:

   a) more acceleration at high energy → flatter spectrum

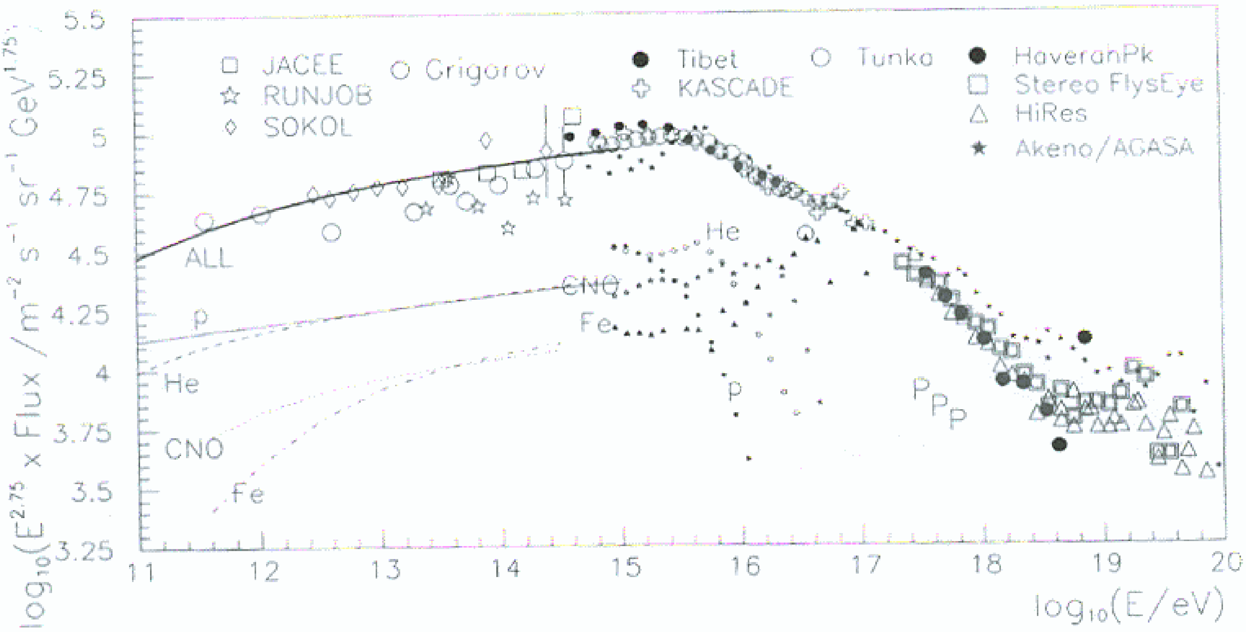
   b) High self-generated B field (Bell & Lucek)
   → *a knee!*

7. Where does this leave us?
   Formation of spectral slope?
   Understanding transport of CR

8. New features to look for
   Spectrum curvature in TeV gamma rays
   Composition close to knee

1. What is the energy spectrum of Cosmic Rays?

$J(E)\ /\ E^{-2.75}$ plotted --



From $<10^{10}$ eV to 4×10^{15} eV, $dN/dE \sim E^{-2.69}$

↑ the "Knee"

↑ (after correcting for fragmentation losses)

— Falls more steeply above this energy

Main nuclei have virtually same distribution in rigidity

↑= E/charge

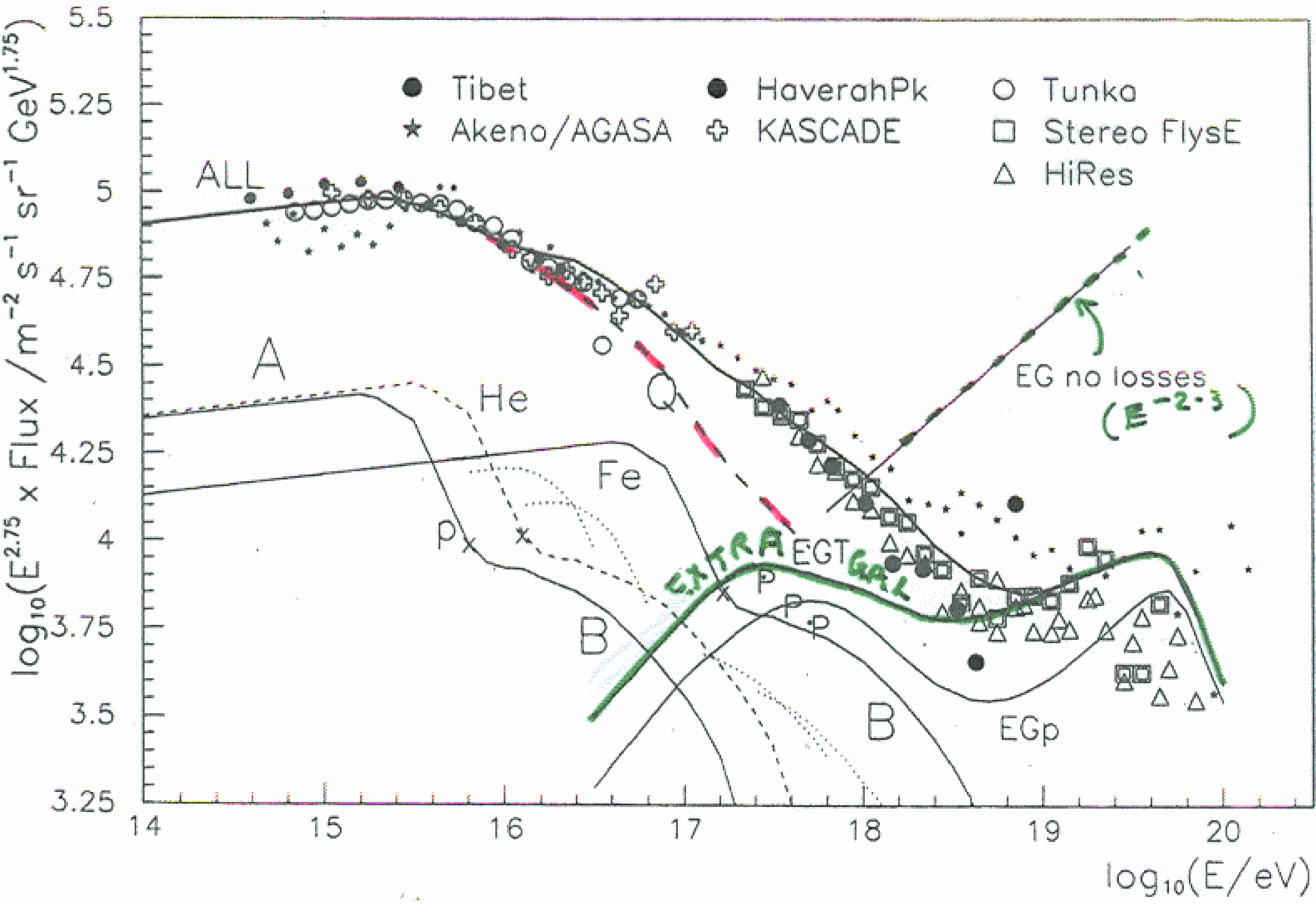
There is probably a sharp drop near a rigidity of 3×10^{15} V,

then a component extending just past 10^{17} V,

(-- then extragalactic cosmic rays)

↓

Spectra of cosmic-ray nuclei if all galactic c.r. have same dependence on rigidity ($\propto \frac{E}{Z}$).



Q = sum without "B" component

Extragalactic cosmic rays more numerous than Galactic cosmic rays above about 10^{18} eV

(but extragalactic cosmic rays not discussed here)

2. Crude explanation of the spectrum $E^{-2.7}$

Sources: Pcles accelerated at SNR blast waves

→ *source spectrum* -

particles released into Galaxy at rate $Q \propto E^{-2.1}$

($E^{-2.0}$ ideally, for simplest diffusive shock acceleration)

& trapping lifetime -

pcles wander in Galaxy for time $T_{residence} \propto E^{-0.6}$

(Deduced from fragmentation damage sustained, using "leaky box" model of propagation)

☺ → Hence spectrum of resident pcles in galaxy $\propto E^{-2.7}$

But particles cannot be contained in SNR accelerator above "knee" rigidity

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BUT . . .

3. BUT: high-energy CR (10^{12}–10^{17} eV) raised problems

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a) CR almost isotropic → Lifetime T in Galaxy cannot fall so fast

If "grammage" ($\propto T_{residence}$) $\propto E^{-0.6}$,
outflow from Galaxy very fast above 10^{15} eV
→ Anisotropy ~>4% at 10^{15} eV, >40% at $1.5\text{x}10^{17}$ eV,
cf *< 0.4%* *< 2% observed*
. . but if $T_{residence} \propto E^{-1/3}$ (more understandable),
→ anisotropy ~ 0.3% at 10^{15} eV, ~1% at $1.5\text{x}10^{17}$ eV,

. . but then, we require source spectrum $\propto E^{-2.36}$ to give
CRs $\propto E^{-2.69}$ in Galaxy.

☹ 💣 → spectral shape problem

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b) Maximum energy possible from SNR accelerators seemed
<< maximum E of galactic CR

☹ . . . $E_{max} < 10^{14}$ eV xZ ← Lagage & Cesarsky;
Ellison, Baring, Reynolds . .
. . . until Bell & Lucek complicated the magnetic field picture,

☺ → but good news here!! (see below)

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c) Low level of (TeV) gamma emission from SNR gas
TeV gamma-rays not seen at the level expected
from very simple arguments (updated "DAV")

💣 ? . . . Cas A flux 30-50 times below this ↑

4. Power requirement (revisited)

Some methods of deriving the CR energy supplied to the Galaxy per century involve some very poorly known estimates.

Rate of production of
protons in energy range 10 – 100 GeV
. . . in range 4 – 12 kpc from Galactic centre

can be estimated relatively well.

2/3 of SN lie in this distance range, hence, total Galactic power supplied to nuclei by SNR in this rigidity range (after allowance for other nuclei) . .

(alternative spectral slopes of released nuclei do not result in very different total power input when scaling up from this decade of rigidity)

→ IF there are 3 SNR per century in the Galaxy (the biggest source of uncertainty) each one has to put 16% of its 1 foe of explosion energy into CR.

→ Conversion of energy to CR has to be quite efficient!

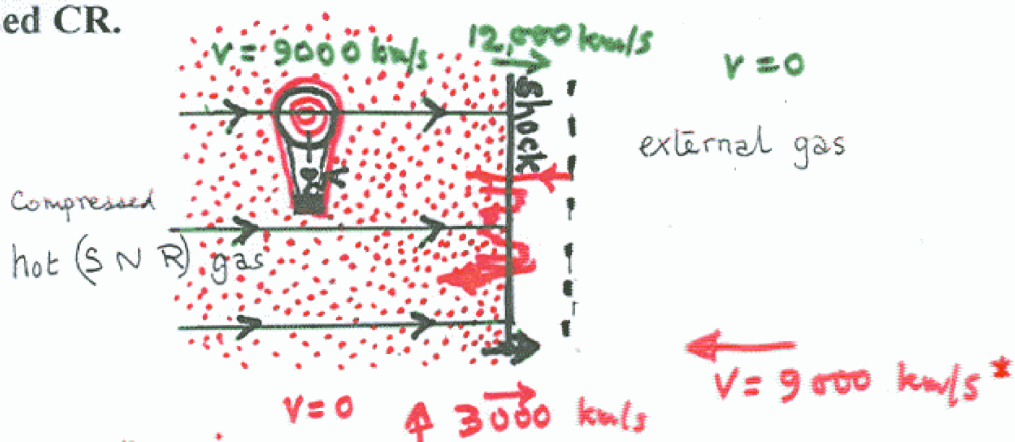
5. Efficient shock acceleration in SNR:

(Shocked gas is hot but non-Maxwellian)

Not easy to see how less than ~ half the SNR hot gas energy goes into CR, unless the magnetic field somehow prevents most particles from re-crossing the shock.

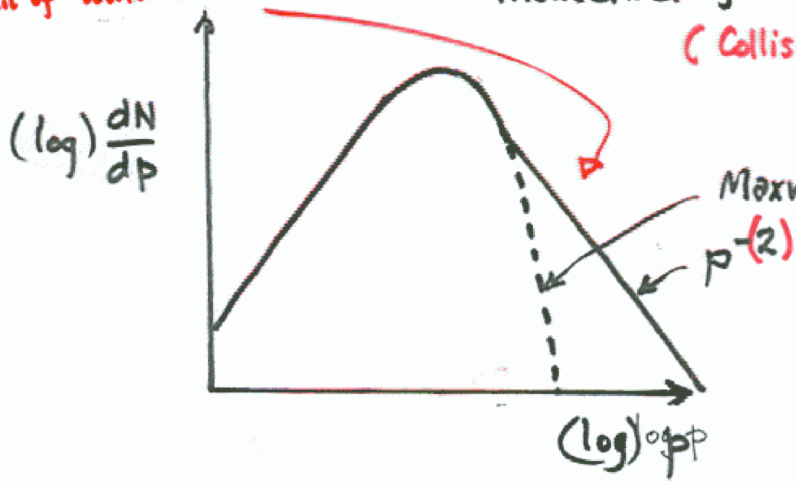
In this case, after adiabatic expansion, one might crudely expect ~ 1/3 of E_{SN} to become ordinary thermal energy, 1/3 relativistic energy, and 1/3 bulk kinetic energy.

. . . hence a reasonable prospect of getting 16% of E_{SN} into released CR.



(* Gas ions still moving at 9000 km/s — but random directions — after shock)
→ many cross back & form tail of distribution

momenta of ions in hot gas.
(Collisionless shock)

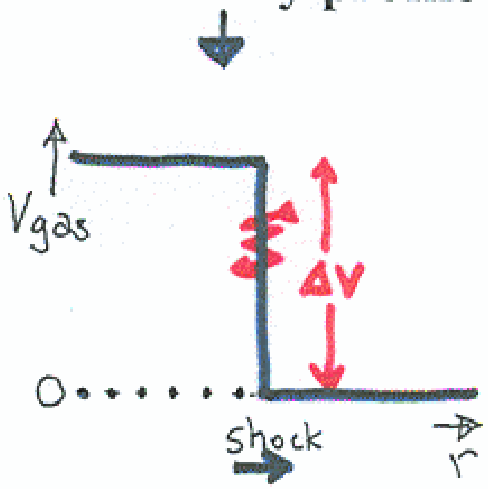


6. Acceleration with cosmic-ray modified shock

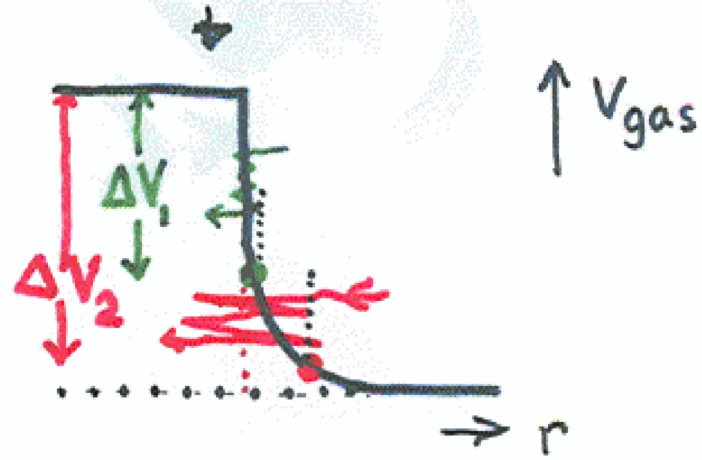
a) More acceleration at high energy.

As relativistic particles are now expected to supply a large part of the pressure in the hot gas, and some of them are diffusing ahead of the shock, .. the interstellar gas receives some pre-compression:

Velocity profile



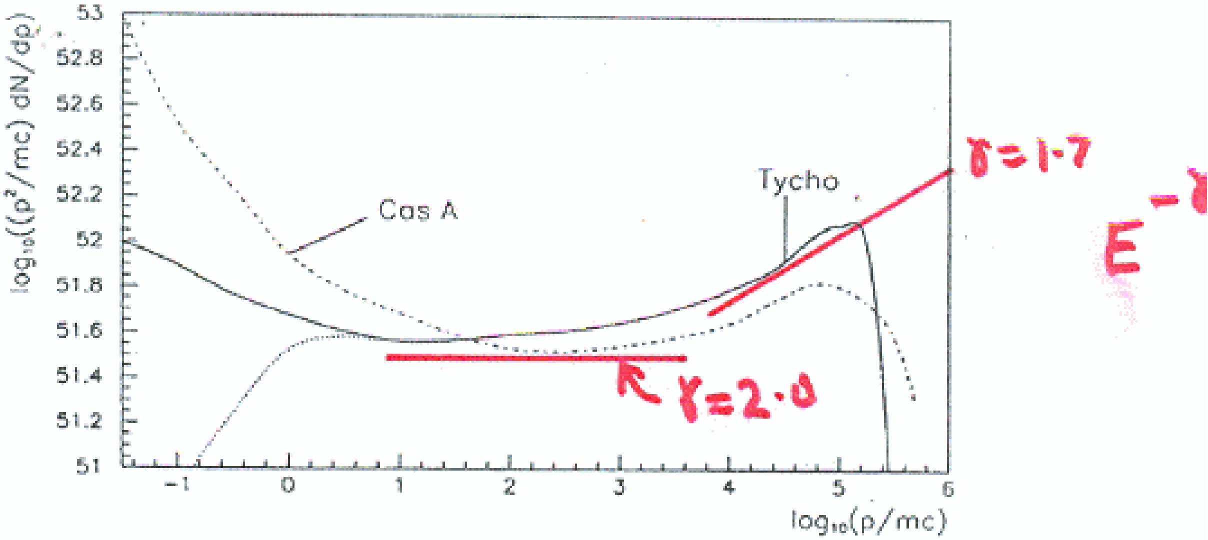
becomes



High-E particles diffuse right across a bigger velocity step and gain more energy

→ flatter spectrum at highest E ("curved spectrum")

Predicted $p^2 dN/dp$ in Tycho, Cas A:



☹ Not seen in CR spectrum

(∴.What about TeV gammas?)

(Acceleration with cosmic-ray modified shock) . . .

b) High self-generated magnetic field (Bell & Lucek)

Bell & Lucek argued for a very rapid process of magnetic field generation (amplification of noise) just ahead of the shock. . highly contorted field (→Bohm scattering), with

$$B \propto V_{shock}\,\rho_{gas}^{\;1/2} \;\times\; \underbrace{[\,P_{cr}/(0.1\,\rho_{gas}V_{shock}^{\;2})\,]^{1/2}}_{[\;]\,\sim\,1 \text{ in efficient shock}}$$

(Though the field generation may be damped for V_{shock} < few 10^3 km/s : Ptuskin & Zirakashvili)

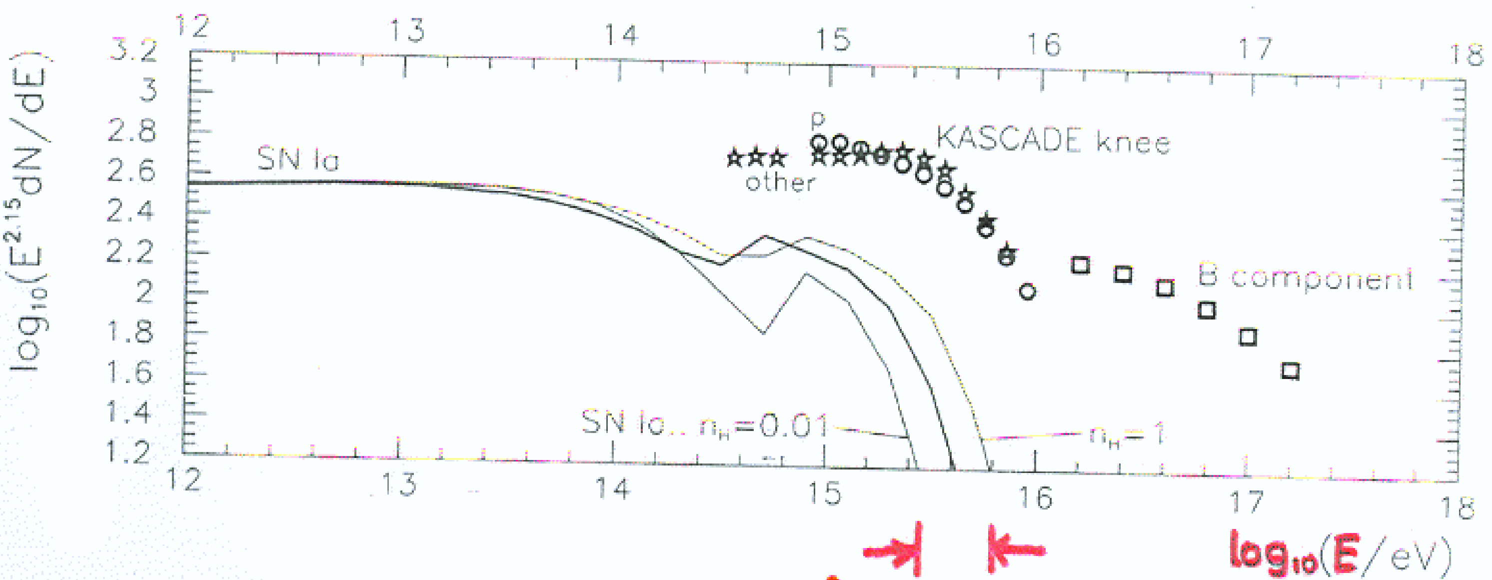
This $V_{shock}\,\sqrt{\rho_{gas}}$ dependence will change the systematics of the maximum energy of particles in SNR . . .

* E_{max} is attained very early (well before "T_0")
  . . . and the energetic particles then escape
* The $\rho_{gas}^{\;1/2}$ dependence almost cancels a dependence $\rho_{gas}^{\;-1/3}$ found for previous models

B not V-dependent

→ using an approximate ('toy") SNR expansion model, I find, for SN Ia (mass 1.4 $M_\odot$ ejected with 1 f.o.e. energy): $=10^{51}$ erg

→A Knee, *independent of ambient B, ρ (almost)*



factor 100 in gas density

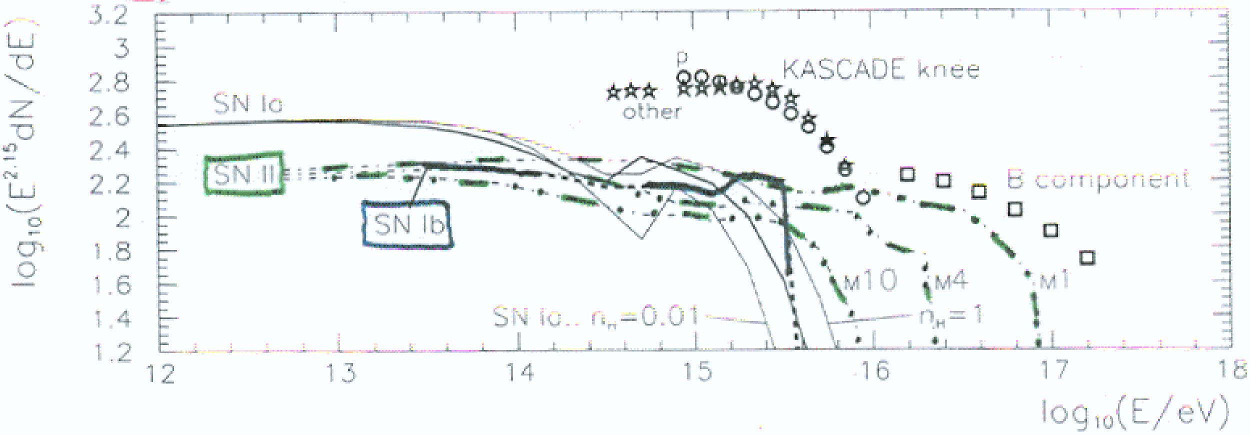
Toy model applied to 3 types of SNR . . .

(model not good after external shell hit in Ib)

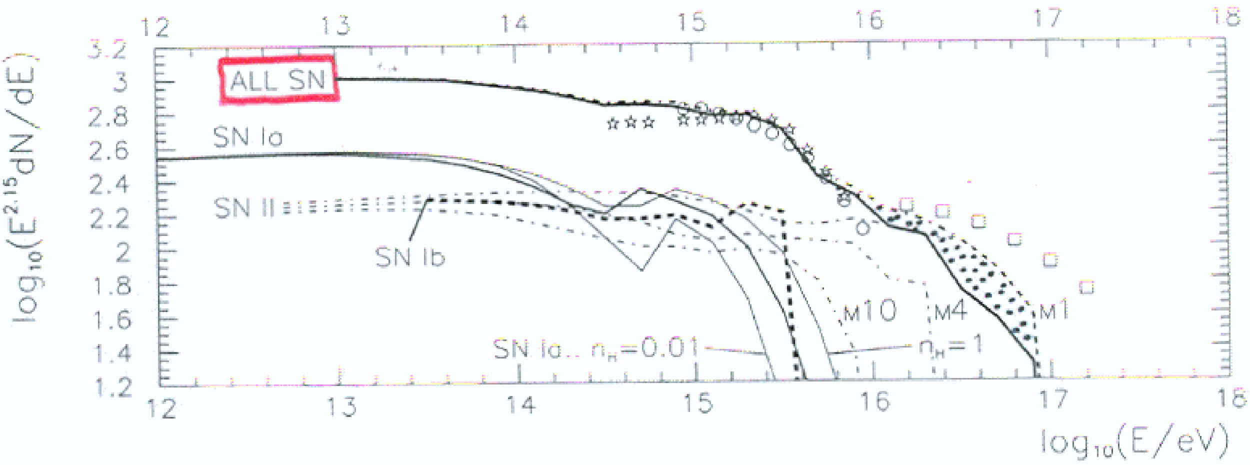
Type Ia (~1/6) explode into medium of constant density
Mass 1.4 $M_\odot$ ejected

- **Type Ib (~1/6) explode initially into very low density hydrogen-free gas, then hit gas shells**
- **Type II (~2/3) many explode into very dense gas wind of red supergiant – Masses ~1 to 10 $M_\odot$ ejected.**

– All (surprisingly) eject 1 f.o.e. energy (10^{51} erg = 10^{44} J)



. . . and a crude addition (Ia (mixture of nH=0.1, 1) + Ib + II mass 10 + mass 4* + mass 1*) (* in 2 different proportions)



☺ *There is a distinct knee!* **– in a reasonable place**

7. Where does this leave us?

- Bell & Lucek may well have removed the E_{max} problem.

- We may need a non-curved spectrum of released CR with slope near $E^{-2.36}$

  (Perhaps related to staged release of the very energetic particles, and low-Mach-number release of lower-E pcles.?)

.. or we need a very different pattern of cosmic-ray propagation, in which we are not in the escape path.

- Was Cas A abnormal in showing such a low TeV gamma-ray flux?

8. New features to look for

* There is an important role for TeV gamma-ray observations, to examine shape of spectrum: is it “curved up”?

* In the picture presented above,

** the particles at the knee **

are produced very early, at ~ 0.1 T_O ,
→ [redacted] strong inner shock :
it could accelerate nuclei ejected from the SN — rather than nuclei from interstellar gas — which then escape as the field weakens.

So there may be a component rich in heavier nuclei (Fe in the case of type Ia) just around the knee.

(At lower energies, particles accelerated by the [redacted] inner shock remain trapped and suffer serious adiabatic deceleration.)

→ a task for KASCADE-GRANDE.